SENSOR LETTERS
Vol. 10, 1075–1080, 2012

RESEARCH ARTICLE

Analysis and Design of a Single-Axis Automatic Solar Tracking and Power Filtering System for Solar Power Generation

Yun-Parn Lee[1,*], Chen Sin-Hong[1], Gau Yau-Quen[1], Wang Kai-Der[1], Shih-Hsin Ma[2], and Jih-Huah Wu[3]

[1] *Department of Electronic Engineering, Ming Chuan University, Guaisan, Taoyuan County, 333, Taiwan, ROC*
[2] *Department of Photonics, Photonics, Feng Chia University, Taichung, Taiwan, ROC*
[3] *Department of Biomedical Engineering, Ming Chuan University, Guaisan, Taoyuan County, 333, Taiwan, ROC*

(Received: 28 May 2011. Accepted: 5 September 2011)

A solar tracker is a device that orients its payload, in this case photovoltaic panels, toward the sun. The solar panels are affected by the incident angle. In other words, when directly exposed to Sunlight, they can achieve performance of one hundred percent, however, when this angle decreases to 45 degrees, only approximately 70 percent of the incident energy is left. Therefore, we design an automatic tracking system, which, like a sunflower, always faces the sun, so that the power generation efficiency can be maintained at the highest point. Most of the existing studies have focused on mechanical and optical designs for either one, two, or three axis tracking systems. In this paper, we present the tracking mathematics of the sensors and controlling motor drive. The power filter is a very important part of a completed solar generation system. When DC is converted to AC, the system will generate harmonic noise. The incomplete sinusoidal signals are also due to harmonics and lossless power. We will re-design a power filter device to generate perfect output sinusoidal waves. In our study, we will show the completed design process, circuit diagrams and final test results.

Keywords: Single Axis Solar Tracking, Sun-Earth Orbit Calculation, Solar Power Concentration, Solar Power Filtering.

1. INTRODUCTION

The Sun generates huge amounts of energy, however, because of the distance from the Sun to the Earth, only 1/2.2 billion parts of that energy will reach the earth, of which 19% will then be absorbed by the atmosphere, 30% will be reflected back into space, and the remaining 51% will reach the Earth's surface. The unit area of the energy, the solar irradiance, is calculated yb exposure to solar radiation for a certain period of time. There are three factors affecting the solar irradiance, the elevation angle of the Sun, the Sun-Earth distance and the duration of sunshine hours. The Sun's elevation angle is the angle between the ground and the solar rays, and is proportional to its intensity or irradiance. The intensity of the Solar is proportional to the duration of the sunshine. However, this will be in different in different areas and seasons. In addition, rainy days also have a major impact on the duration of the sunshine hours. Figure 1 shows the greatest number of rainy days in March in Tao Yuan so the length of sunshine time will be relatively small, while Figure 2 illustrates the most sunshine hours in July. In section 2, we will show how single axis solar tracking is sufficient for locations near the Earth's equator.

2. SOLAR TRACKING DYNAMICS – SINGLE AXIS TRACKING NEAR THE EARTH'S EQUATOR

The significance of the ecliptic is evident if we examine the Earth's orbit around the Sun, as shown in Figure 3. The analemma and the Equation-of-Time are a result of the sum of the effects of the Earth's elliptical orbit around the Sun and the tilt of the Earth's axis in relation to the plane of its orbit around the Sun. Figure 4 shows the effect of

*Corresponding author; E-mail: yplee@mail.mcu.edu.tw

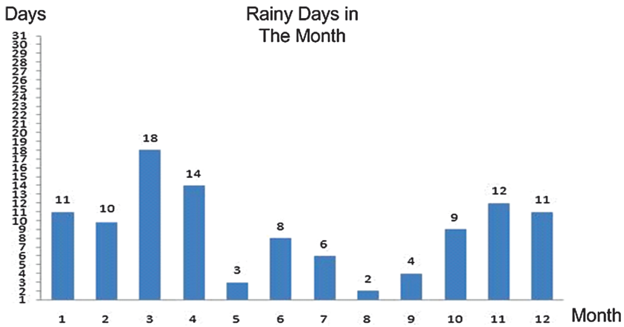

Fig. 1. Rainy days in the Tao Yuan area.

this summation. The equatorial coordinate system and horizontal coordinate system are used for these two celestial coordinates to identify the location of the Sun in the celestial sphere. In the equatorial coordinate system, the hour angle and declination angle are used to identify the location of the Sun. The hour angle is expressed by ω, and can be calculated as the time difference from noon (hours) multiplied by 15 degrees. The declination angle is the angle between the connection from the center of the Sun and the Earth's center to the equatorial plane, commonly expressed as δ. The value of the declination angle has nothing to do with location, but is only matter of the day of the year. The declination angle is calculated as follows:

$$\delta = 23.45 \sin\left(360 \times \frac{284+n}{365}\right) \tag{1}$$

where n is the yearly date. For an example, for September 22, n is 265. In the horizontal coordinate system, we usually calculate the elevation angle and azimuth angle to define the position of the sun relative to the Earth's surface. However, due to the difference in location of the earth at different times throughout the year, the elevation angle and azimuth angle will be different.[1,2] The angle between the Sunlight and the Earth's surface normal is called the zenith angle θ_Z. The angle between sunlight and projection on the horizontal line is called attitude angle α_S. The attitude angle and the zenith angle has following relationship:

$$\theta_Z + \alpha_S = 90° \tag{2}$$

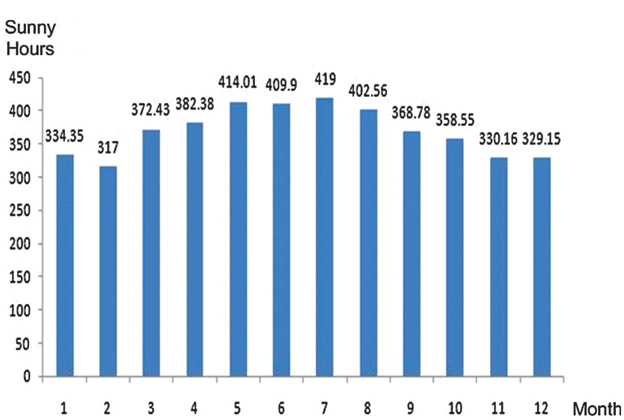

Fig. 2. Sunshine hours in the Tao Yuan area.

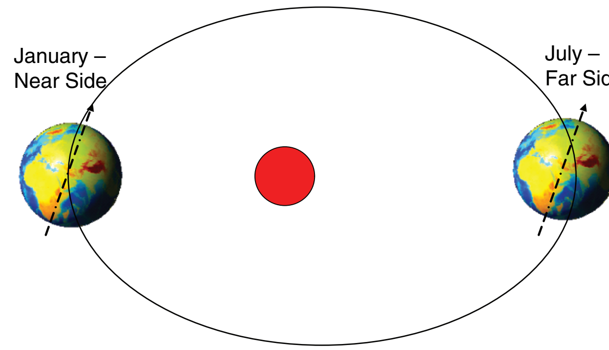

Fig. 3. Sun and earth orbital map.

The angle between the projection of the Sunlight on the ground and the horizontal south line is called the azimuth direction angle γ_S. Therefore, we have

$$\sin\alpha_S = \cos\theta_Z = \sin\varphi\sin\delta + \cos\varphi\cos\delta\cos\omega \tag{3}$$

At noon time, $\omega = 0$ and the above relationship can be simplified as

$$\sin\alpha_S = \sin\left[90° \pm (\varphi - \delta)\right] \tag{4}$$

We can use Taoyuan, Taiwan as an example to compute the Sun's position. On September 22, what is the attitude angle at noon (12PM), and 3PM in the afternoon? Since

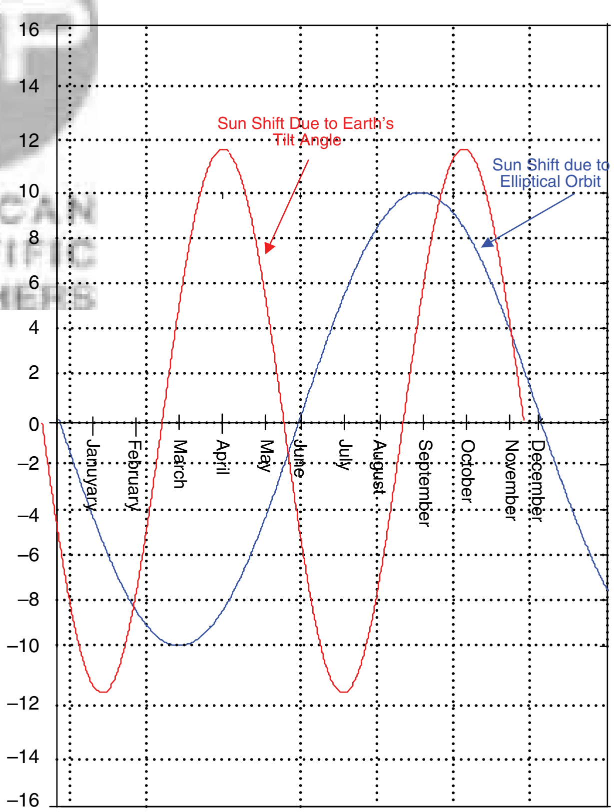

Fig. 4. Sun shift due to the Earth's tilt in an elliptical orbit around the Sun.

Taoyuan's latitude is 24.58° $\delta = -0.6°$, the hour angle at noon (12PM) is 0°, and at 3PM, the hour angle is 45°, therefore, the attitude angle α_S at 12PM is

$$\begin{aligned}\alpha_S &= 90° - \varphi + \delta \\ &= 90° - 24.55° + (-0.6°) \\ &= 64.82°\end{aligned}$$

then at 3PM, the attitude angl α_S can be computed as follows:

$$\begin{aligned}\sin\alpha_S &= \sin(24.58°)\sin(-0.6°) + \cos(24.58°) \\ &\quad \times \cos(-0.6°)\cos(45°) \\ &= 0.6386\end{aligned}$$

$$\sin^{-1} 0.6386 = 39.69° \tag{5}$$

We can also calculate the Azimuth angle using following relationship:

$$\sin\gamma_S = \frac{\cos\delta\sin\omega}{\cos\alpha_S} \tag{6}$$

$$\cos\gamma_S = \frac{\sin\alpha_S\sin\varphi - \sin\delta}{\cos\alpha_S\cos\varphi} \tag{7}$$

Let us again compute the Azimuth angle for Tao Yuan County at 2PM on September 22. We must first find the attitude angle:

$$\begin{aligned}\sin\alpha_S &= \sin(24.58°)\sin(-0.6°) + \cos(24.58°) \\ &\quad \times \cos(-0.6°)\cos(30°) \\ &= 0.7831\end{aligned} \tag{8}$$

$$\sin^{-1} 0.7831 = 50.55° \tag{9}$$

$$\sin\gamma_S = \frac{\cos\delta\sin\omega}{\cos\alpha_S}$$

$$\begin{aligned}\sin\gamma_S &= \frac{\cos(-0.6°)\sin(30°)}{\cos(51.55°)} \\ &= 0.804\end{aligned}$$

$$\sin^{-1} 0.804 = 53.51°$$

Therefore, the Azimuth angle at 2PM on September 22 at Tao Yuan is 53.51°.

From the above calculation, since the attitude angle at sunrise and sunset is 0°, therefore we have.

$$\cos\omega_S = -\tan\varphi\tan\delta \tag{10}$$

$$\omega_s = \omega_{sr},\ (-\omega_s) = \omega_{ss} \tag{11}$$

where ω_{sr} stands for the hour angle during sunrise, ω_{ss} stands for the hour angle during sunset. From the above calculation we know that at the same location, the hour angle of the sun at sunrise and sunset is symmetrical.

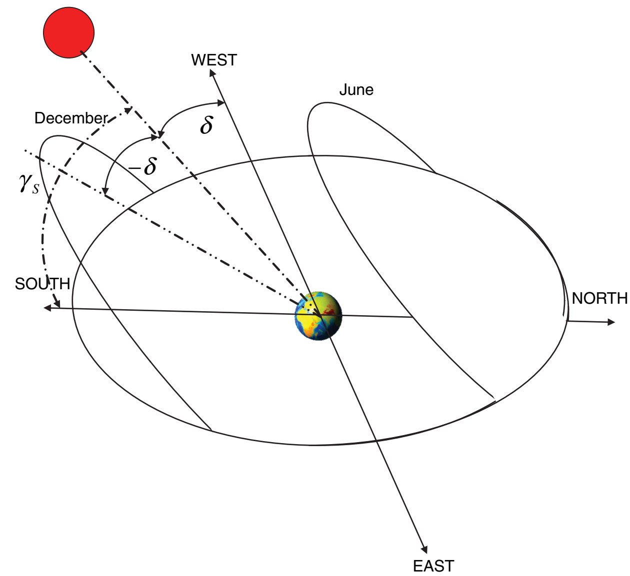

Fig. 5. Sunpath diagram for the four seasons in a year.[3,4]

Therefore, we prove that we can easily design a single axis solar tracking system with a movable base in order to generate the maximum solar power output. The movable base can change its position (or orientation angle) slightly during the four seasons.

3. SINGLE AXIS SOLAR TRACKING CONTROL CIRCUIT DESIGN

The CDS photo resistors[5] are installed on the either side of a solar panel to determine whether or not there is a shift in the Sunlight, which are then connected to a circuit, as shown in Figure 7. Due to difference in the angles of

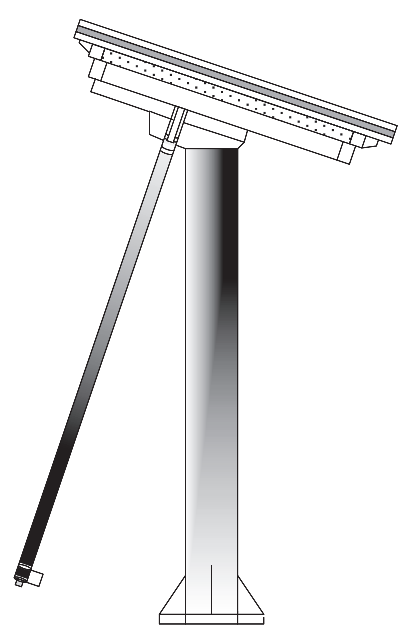

Fig. 6. Single axis solar tracking system.

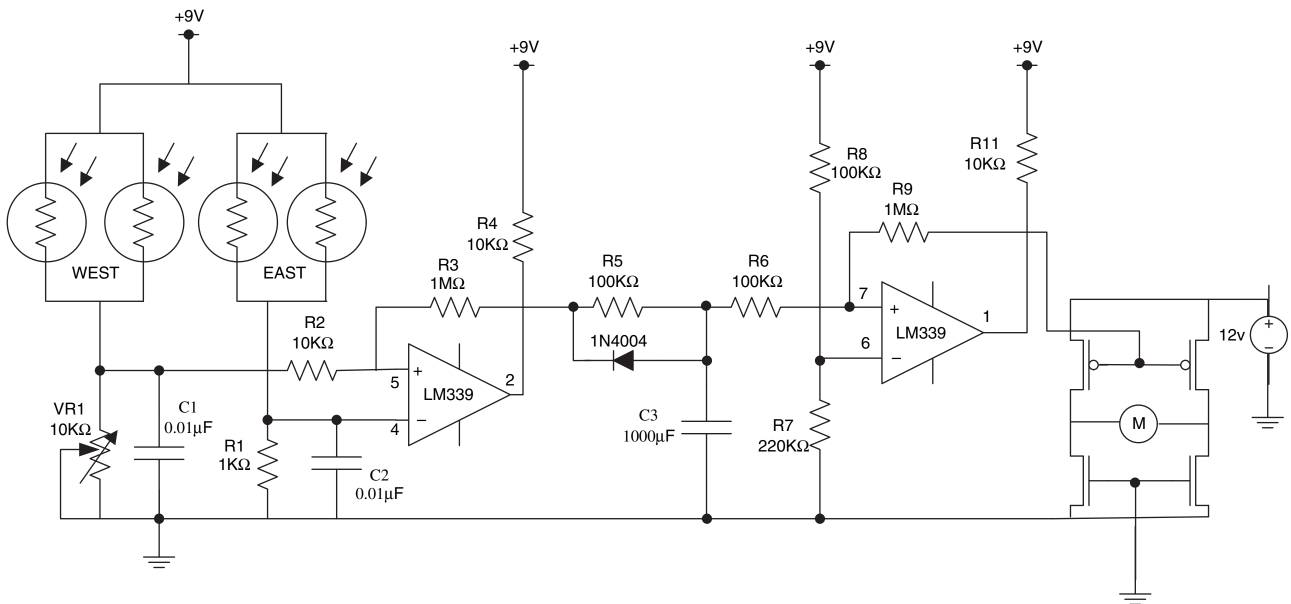

Fig. 7. Single axis solar tracking circuit.

the Sunshine, the intensity of the light on the solar panels will be different, leading to a difference in voltage. The circuit will determine the direction of the bias, and finally the bias voltage can drive a motor to rotate the panels in order to track the Sun's movement throughout the day. We applied 5 V to the photosensitive resistors, and then connected them to an operational amplifier comparator. The comparator's other end was connected to the input voltage of 2.5 V. When there is no voltage difference the comparator outputs a zero signal. At this time, on the right hand side of the circuit, the PMOS is not conductive, and the nMOS is conductive, therefore, the voltage across the motor is equal to the ground potential, and the motor will not rotate; however, when the a difference in voltage occurs, the comparator outputs a positive voltage signal. At this time, nMOS is not conductive but pMOS is conductive. Therefore, 12 V voltage is connected to the motor to rotate the motor until the voltage difference reduce to zero.

(a)

(b)

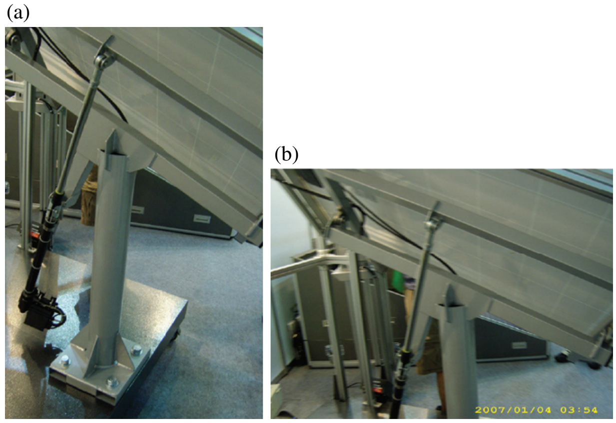

Fig. 8. (A)–(B). Fully assembled single axis solar tracking station.

4. SOLAR POWER FILTERING SYSTEM

Due to the rapid development of power electronics technology, high-power switching devices have been successfully developed. Power electronics have become the most important harmonic sources. Not only does differences in voltage have a serious impact on the systems, but also reduces the circuit power quality. Therefore a power electronic filter is needed, which mainly uses harmonic suppression and reactive power compensation. An ideal circuit should provide a voltage with single fixed frequency, with voltage amplitude within the allowable range. However, harmonic pollution of the circuit waveform causes deterioration in the quality of the circuitry, so that the electrical equipment on the same circuit may be severely affected.

In order to compensate for the reactive power and to filter the power harmonics, shunt capacitors, or a combination of shunt capacitors and inductors are often needed.[6] The harmonic frequencies are normally higher than the line frequency, which leads to an increase in the inductive reactance of the system but a decrease in the capacitive reactance It is also possible to produce LC resonance. The

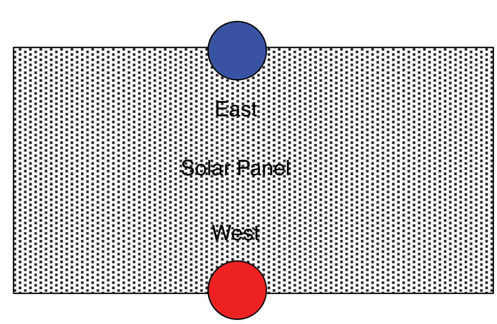

Fig. 9. Solar panel integrated with CDS photosensors.

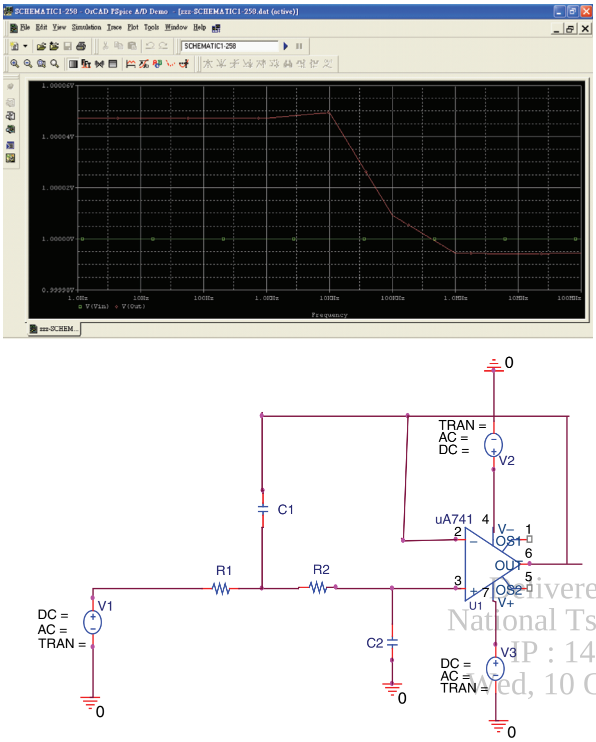

Fig. 10. Low pass filtering circuit diagram and PSpice Simulation for Solar power generation.

resonant amplification of harmonic currents may burn the capacitors or inductors.

There are three factors affecting the reactive power compensation in the power supply system:

(1) the use of passive and active power filters for power supply circuits for reactive power compensation. Striving for a measured power factor of more than one, can also improve the quality of power supply circuit.

(2) The application of a dynamic reactive power compensation device in the power distribution and transmission system can improve system stability, as well as increase transmission capacity.

(3) Reactive power compensation in the power systems can improve the power factor of the equipment and this can reduce the harmonics and the equipment capacity.

There are three types of electronic active filters:

(1) the electronic active low pass filter;

(2) electronic high pass filter;

(3) electronic band pass filter.

Figure 10 shows a schematic representation of an electronic active low-pass filter. The filter is composed of an operational amplifier and RC filters. This is a second order active low pass filter, therefore, the active low pass filter has both a filtering function and an amplification function. The gain on the operational amplifier is one. The

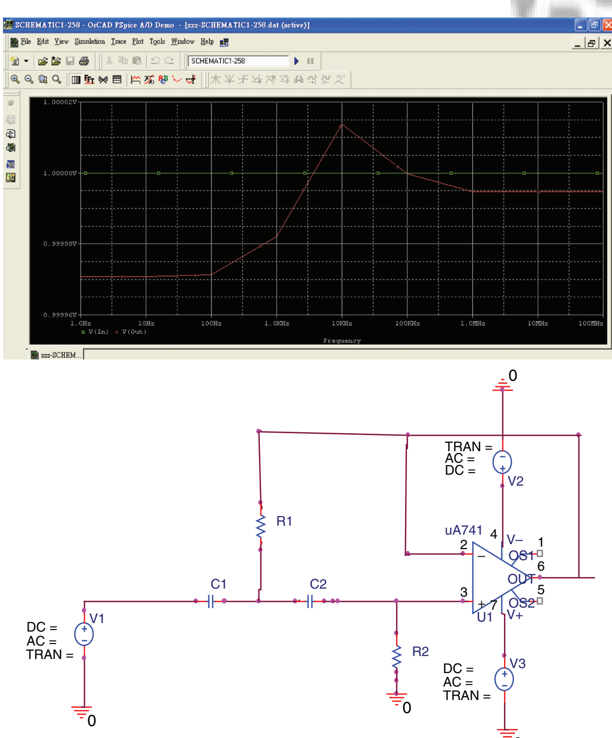

Fig. 11. High pass filtering circuit diagram and PSpice simulation for solar power generation.

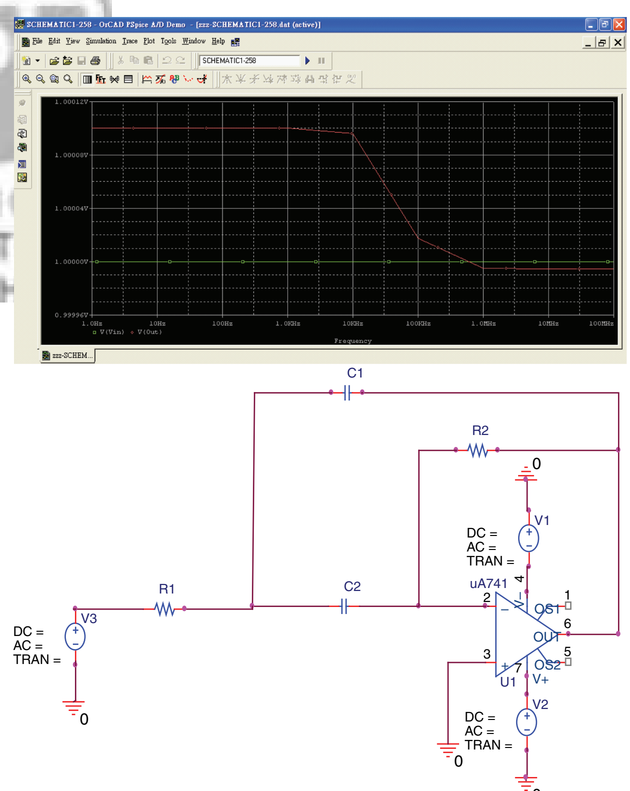

Fig. 12. Band pass filtering circuit diagram and PSpice simulation for solar power generation.

RESEARCH ARTICLE

cut-off frequency f_o can be computed using the following equation:

$$f_o=\frac{1}{2\pi RC},\ \ R=R_1=R_2,\ \ C_1=2QC,\ \ C_2=\frac{C}{2Q} \quad (12)$$

Figure 11 shows a schematic representation of an electronic active high-pass filter. It is the same as in the low pass active filter, except that the positions of the resisters and capacitors are exchanged. The cut-off frequency f_o can be computed using the following equation:

$$f_o=\frac{1}{2\pi RC},\ \ C=C_1=C_2,\ \ R_1=\frac{R}{2Q},\ \ R2=2QR \quad (13)$$

Figure 12 shows a schematic representation of an electronic active band-pass filter. The cut-off frequency f_o can be computed using the following equation:

$$f_o=\frac{1}{2\pi}\sqrt{\frac{1}{C_1C_2R_1R_2}},C=C_1=C_2,R_1=\frac{R_2}{4Q^2}$$

$$R_2=\frac{Q}{\pi f_o C} \quad (14)$$

5. CONCLUSION

In this paper, we prove mathematically that with a simple movable base, a single axis solar tracking station can perform excellent solar tracking. We present our design for the mechanical assembly and electronics of a single axis solar power control circuit in section 3. We also illustrate the principles of operation of the power filtering technology for the solar power generation in Section 4.

References and Notes

1. S. Krauter, Solar Power Generation-Photovoltaic Energy System, German (**2008**).
2. J. E. Braun and J. C. Mitchell, *Solar Energy* 31, 439 (**1983**).
3. http://www.phy6.org/stargaze/Scelsph.htm.
4. G. M. Masters, Renewable and Efficient Electric Power Systems, John Wiley & Sons, Inc. (**2004**).
5. http://en.wikipedia.org/wiki/Photoresistor.
6. Q. Shu-Kee et al., Power Electronics Filtering Technology and Its Application, Electronic Industry Publisher, Chinese (**2008**).